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Analysis of liner performance using the NASA Langley Research Center Curved Duct Test Rig

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ABSTRACT

The NASA Langley Research Center Curved Duct Test Rig (CDTR) is designed to test aircraft engine nacelle liner samples in an environment approximating that of the engine on a scale that approaches the full scale dimensions of the aft bypass duct. The modal content of the sound in the duct can be determined and the modal content of the sound incident on the liner test section can be controlled. The effect of flow speed, up to Mach 0.5 in the test section, can be investigated. The results reported in this paper come from a study to evaluate the effect of duct configuration on the acoustic performance of single degree of freedom (SDOF) perforate-over-honeycomb liners. Variations of duct configuration include: asymmetric (liner on one side and hard wall opposite) and symmetric (liner on both sides) wall treatment; inlet and exhaust orientation, in which the sound propagates either against or with the flow; and straight and curved (outlet is offset from the inlet by one duct width) flow path. The effect that duct configuration has on the overall acoustic performance is quantified. The redistribution of incident mode content is shown, in particular the mode scatter effect that liner symmetry has on symmetric and asymmetric incident mode shapes. The Curved Duct Test Rig is shown to be a valuable tool for the evaluation of acoustic liner concepts.

1. Introduction

Despite significant strides that have led to aircraft engine noise reduction, notably the high bypass ratio engine, the engine is still a dominant noise source in most flight regimes [1], producing tonal noise at the Blade Passage Frequency and its harmonics as well as broadband noise. As noise reduction technologies become incorporated into airplanes, the demand for more sophisticated technologies grows. Evaluation of these new technologies on full scale aircraft is costly; and analytic models, while steadily improving in accuracy, have not yet reached the level where they can reliably predict noise control performance in actual flight conditions. Laboratory ducts are often used to characterize and parameterize sound propagation in and radiation from ducts [2–4] or to assess the performance of noise control treatments [5–7] Chestnutt and Lansing [8] developed a fan rig at NASA Langley Research Center to investigate several inlet noise reduction concepts, including sonic inlet, hybrid (sonic and lined) inlet, inlets with various liner patches, and a refracting inlet. This particular inlet test rig has since been dismantled. When a search of available duct facilities was undertaken, significant drawbacks were revealed: many of the facilities were not open to outside researchers; their designs were not flexible enough to accommodate different duct acoustic treatment configurations; the structure of the sound field either was not controlled or was limited to plane waves. Thus the decision was made to develop a test rig in house at NASA Langley Research Center.

The Curved Duct Test Rig (CDTR) is a research tool whose purpose is to improve the understanding of the behavior of acoustic treatment in an environment such as the aft bypass duct. The aft bypass duct is an annulus that has a curved flow path to follow the contour of the turbine. This annular duct is often split into two semi-annular sections by pylons or bifurcations. The CDTR is a rectangular cross-sectioned representation of the aft bypass duct of a commercial aircraft engine. In the CDTR, this semi-annular cross-section is 'unwrapped' to a rectangular cross-section such that the vertical dimension of the CDTR corresponds to the circumferential and the horizontal dimension corresponds to the radial dimension of the bypass duct. Even though the cross-section is rectangular, the design of the rig accommodates curvature in the flow path in order to assess the effect of this design feature, with

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Nomenclature

a, b	duct width, duct height
$\{A\}$	mode coefficient vector
c_0	sound speed
χ	normalized liner reactance
d	perforate hole diameter
ΔdB	attenuation
f	frequency
$\{\phi\}$	mode sound power vector
h	honeycomb core depth
i	$\sqrt{-1}$, unit imaginary number
$I(x, y, z)$	sound intensity at (x, y, z) in hard wall duct
k	ω/c_o, free space wavenumber
$\kappa^{\pm}$	axial wavenumber
L	total number of microphones in the microphone array
λ	wavelength
m, n	vertical and horizontal mode order
M_0	mean flow Mach number
P	sound power level, dB re 10^{-12} W
p	acoustic pressure
θ	normalized liner resistance
ρ_0	density of air
$\Re$	real part of a complex number
T	modal response matrix
u	axial component of acoustic particle velocity
ω	angular frequency
x, y, z	horizontal, vertical, and axial coordinate
Z	liner impedance
ζ	normalized liner impedance

Superscripts

+	positive-traveling wave component
−	negative-traveling wave component
T_r	transpose of a matrix
∗	complex conjugate

Subscripts

n	horizontal mode order
m	vertical mode order
u	location in the hard wall duct upstream of the liner test section
d	location in the hard wall duct downstream of the liner test section
opt0	optimum at no flow condition
opt$M$	optimum with flow on a Mach M

the aim of determining whether use can be made of curvature to enhance liner performance. The test section cross-section of the CDTR is rectangular, rather than annular, in order to facilitate the design and manufacture of candidate duct liner configurations. Because of the similarity of the modal sound distribution between the bifurcated annular duct (typical of an aft bypass duct) and a rectangular duct, it is felt that the results obtained in the rectangular cross section duct can provide data that are applicable to engine installations. The experimental rig is relatively large, the test section dimensions are scaled to between 25% and 100% of the bypass duct of most modern engines. Air flow through the duct is designed to be typical of a bypass duct and flow speeds to Mach 0.50 can be achieved. The experiments discussed in the current paper were conducted in the CDTR at a flow speed of Mach 0.275, which is intended to show the effect of flow on liner acoustic performance. It is expected that the experimental facility can provide data that validate duct noise control techniques and that can be used to enhance the capability of the computational models to estimate noise reduction.

Because of the importance of the tonal component of fan noise, much work has been devoted to studying the generation and propagation of fan tones in a duct. Heidmann et al. [9] performed an experiment in which a number of uniformly-spaced obstructions were placed in the duct upstream of the rotor in order to generate a specific mode structure in the engine inlet. Rice and Heidman [10] showed that the modal structure of the sound in the duct also determines the directivity of far field noise propagation; and Thomas et al. [11] demonstrated that the far field noise radiation can be related back to the modal structure in the duct. Various methods to measure noise in the engine and decompose it into the modal structure have been developed; including a rotating rake of microphones [12], surface-mounted microphones in the inlet [13], or a duct extension [14]. The CDTR uses two fixed arrays of surface-mounted microphones, one in a hard wall duct section upstream of the liner test section and one in the hard wall duct downstream. The microphones are distributed axially and on all four surfaces of the duct. A mode decomposition methodology has been developed to break the sound in the duct into its upstream- and downstream-propagating modes.

Many applications of control systems in ducts have been developed to reduce the tonal noise caused by interaction of rotor wakes and obstructions, either at the source of generation [15–17] or within the duct along the propagation path. These latter applications used secondary sources (loudspeakers) to simulate and control the interaction noise. Thomas et al. [18] utilized a time-domain controller, while Gerhold [19] developed a controller in the frequency domain. Smith et al. [20] discuss the use of multiple circumferential arrays of loudspeakers to control radial as well as circumferential modes. In the CDTR, the goal is not to cancel fan noise but to provide a known, controllable source for fundamental duct propagation and treatment experiments. Similar research was conducted in a spinning mode synthesizer, which utilized an array of circumferentially-mounted loudspeakers in a 0.305 m diameter duct as described by Palumbo [21]. The control sources (loudspeakers) in the spinning mode synthesizer were distributed circumferentially at one axial station and specified duct modes were obtained in the duct by controlling the amplitudes and phases to the loudspeakers. This arrangement permitted high controllability of the circumferential modes but compromised controllability of the radial modes. The adaptive feedforward control system used in the CDTR is designed to drive sound in a target mode at a specified frequency, and to suppress other modes that are cut on at that frequency. The control sources are distributed on all four sides of the duct at two axial locations, so that control is achieved in both cross dimensions of the duct.

The acoustic treatment most commonly used to control engine noise, both in inlet and exhaust ducts, is the locally reacting liner. Such a liner typically consists of a perforated sheet over a honeycomb core. This is backed by a solid sheet to form an array of Helmholtz resonators that resonate at a fixed frequency, both absorbing engine noise and reflecting it back toward the source to inhibit noise radiation toward the ground. Liners add mass and induce drag, both of which increase fuel consumption. The economic considerations favor minimizing the amount of liner while noise con-